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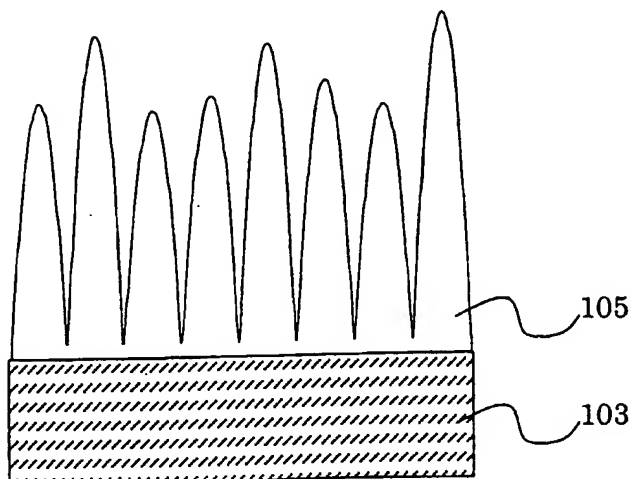
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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: **MICROLENS ARRAYS HAVING HIGH FOCUSING EFFICIENCY**



(57) Abstract: Microlens arrays (105) having high focusing efficiencies are provided. The high focusing efficiencies are achieved by accurately producing the individual microlenses making up the array at high fill factors. Arrays of positive microlenses are produced by forming a master having a concave surface-relief pattern (101) in a positive photoresist (21) using direct laser writing. Through this approach, the problems associated with the convolution of a finite laser beam with a desired profile for a microlens are overcome. The microlens arrays of the invention have focusing efficiencies of at least 75%.

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incoherent light for projection and transmissive displays, among other applications.

15 II. DEFINITIONS

The following definitions are used herein:

A "microlens array" is an array of microlenses and an associated array of unit cells, with one microlens being associated with each unit cell. The microlenses of the present invention can have any desired
20 configuration and can be formed on, for example, a supporting "piston" of the type disclosed in commonly assigned U.S. Patent Application No. 60/222,033 which was filed on July 31, 2000 in the names of G. Michael Morris and Tasso R. M. Sales and is entitled "Structured Screens for Controlled Spreading of Light," the content of which in its entirety is
25 incorporated herein by reference. Thus, as used herein, the term "microlens" means any microstructure which is capable of focusing light.

The "fill factor" of a microlens array is the ratio of the sum of the areas within the unit cells occupied by microlenses to the sum of the areas of the unit cells.

30 The "focusing efficiency" of a microlens array is the sum of the measured light intensities at the focal points of the microlenses divided by

the sum of the light intensities impinging on the unit cells of the array for an array illuminated along its optical axis by a collimated, substantially spatially incoherent light source, e.g., a collimated white light source. As will be recognized by those skilled in the art, this is a "Strehl-type" definition of focusing efficiency.

Since concave microlenses will typically have virtual focal points (e.g., a plano-concave microlens in air will have a negative power and thus a virtual focal point for collimated light), an auxiliary optical system needs to be used in such cases to produce real focal points whose intensities can be measured. To at least some extent, the auxiliary optical system will reduce the intensities at the real focal points, and those reductions should be taken into account in determining the intensity values for the virtual focal points.

In the case of anamorphic microlenses, the light intensities at each of the focal points of the microlens are included in the sum of the measured light intensities.

III. BACKGROUND OF THE INVENTION

Microlenses are required in many applications, such as light coupling from lasers to fibers, either as single lenses or in array form whereby several beams are focused to several fibers. Other important applications include light diffusion and screens.

Depending on the application, one may require a microlens of accurate profile with controlled focusing properties or, in the case of an array, high quality over most lenses in the array. To focus light efficiently, the lens profile (or sag function) must be fabricated with accuracy typically equal to or better than, for example, $\lambda/4$, where λ is the wavelength of the illumination source.

In addition, particularly for high-density coupling, diffusion, or screen applications, it is often important that the microlenses utilize the entire surface for focusing. In this way, essentially all incident light can be controlled by the array. When the entire useful surface area is employed for focusing, the array is said to possess a 100% fill factor.

boundaries avoid close contact. Because there is a finite distance between the internal boundaries of neighboring lenses, the fill factor for the array is
15 necessarily less than 1 (or 100%).

The difficulty in obtaining efficient closed-packed lens arrays using prior art fabrication methods is due to the inability of those methods to preserve the boundaries of microlenses accurately, particularly for small and strongly focusing lenses.

20 Methods using thermal deformation, such as that disclosed in U.S. Patent No. 5,324,623, are based on volume relaxation and thus cannot control the fusing of material at the internal boundaries between microlenses. With fusion there is distortion that reduces focusing capabilities. Thermal deformation methods are simple to implement but
25 allow limited control of the individual microlens structures.

Other methods, such as those described in U.S. Patent No. 5,300,623, involve the creation of mechanical molds that define receptacles for curable liquids. The liquid is poured into the receptacles and the natural surface tension creates a bowed surface that serves as the microlenses. The mold,
30 with the various receptacles, defines the array arrangement. Due to the inherent limitation of this method in controlling the shape of the microlens

units, its efficiency cannot be optimized for a general application. Other mechanical methods based on the direct ruling of individual microlenses, such as diamond turning, are better suited for the fabrication of individual microlenses rather than arrays.

5 Methods based on ion diffusion processes that provide gradient-index arrays, such as those described in U.S. Patent No. 5,867,321, cannot provide a 100% fill factor, with the region between two neighboring microlenses being typically 20% of the microlens repetition spacing. Gradient-index arrays present a serious limitation for large-volume
10 fabrication due to the intrinsically slow diffusion process.

Processes for producing microlens arrays using direct laser writing in a photoresist are known in the art. See commonly-assigned PCT Patent Publication No. WO 99/64929, Gale et al., U.S. Patent No. 4,464,030, and Micro-Optics: Elements, systems and applications, Hans P. Herzig, ed.,
15 Taylor & Francis, Bristol, PA, 1997, pp. 53-152. The photoresist of choice for such processes is a positive photoresist since compared to negative photoresists, positive photoresists are more widely available, have been subject to more intensive research and development work by photoresist manufacturers, and generally have higher resolution. However, as
20 discussed in detail below, prior to the present invention, it has not been possible to produce arrays of positive microlenses having high focusing efficiencies at high fill factors using positive photoresists.

The present invention addresses the difficulties associated with the prior art by providing methods for fabricating microlens arrays having high
25 focusing efficiencies through accurate microlens fabrication at high fill factors. The array can be arranged in any arbitrary way, such as square, hexagonal, or random. In addition, the methods allow the fabrication of microlenses of arbitrary shape as well as variable focusing power for different directions (anamorphic lenses).

concave microlenses with fill factors greater than 90%, preferably greater than 95%, and most preferably approximately 100% so that the entire useful area of a substrate can be employed for focusing or, more generally, scattering of an illuminating beam.

In connection with these objects, it is also an object of the invention to allow the microlenses of the array to have arbitrary shapes (sag functions) that can vary randomly within the array.

It is a further object of the invention to provide improved methods for using positive photoresists to produce arrays of convex microlenses at high fill factors.

To achieve the foregoing and other objects, the invention provides a fabrication method for producing an array of convex microlenses wherein direct laser writing is used to produce an initial master (initial mold) in a positive photoresist wherein the surface configuration of the initial master is the negative (complement) of the desired array of convex microlenses. That is, the initial master has a concave, instead of a convex, surface configuration. In this way, as discussed in detail below, the problems caused by the finite size of a laser beam and the convolution of such a beam

with the desired profile(s) of convex microlenses are overcome. By overcoming these problems, convex microlens arrays having high focusing efficiencies are achieved.

In general, a high focusing efficiency for an array of microlenses
5 depends on two factors: (1) a high fill factor, and (2) accurate reproduction of the desired lens profiles. Both factors are necessary and neither factor alone is sufficient.

Thus, a high fill factor can be achieved by a process that alters all parts of a resist film, but if the alterations do not correspond to the desired
10 lens profiles, the focusing efficiency of the array will still suffer since the parts of the resist film that have the inaccurate profiles will not focus incident light properly. On the other hand, accurate reproduction of a desired lens profile with the individual microlenses spaced far apart also results in low focusing efficiency, in this case as a result of light passing
15 through the spaces between microlenses.

In accordance with the invention, it has been found that both factors can be addressed by using the concave form to initially write convex lenses in a positive photoresist. In this way, high focusing efficiency through the accurate production of desired lens profiles at a high fill factor is achieved.

20 In accordance with certain preferred embodiments, the invention is practiced by using a substrate typically made of glass to support a first medium to generate an initial master (initial mold), which is later used to accurately replicate the desired microlens array in a cost-effective fashion. More particularly, a photosensitive positive resist film is deposited on the
25 substrate to an appropriate thickness consistent with the desired thickness for the final microlens array. The positive resist is preferably of the low-contrast kind such that, when exposed to light, a smoothly varying surface-relief profile can be produced.

After being deposited on the substrate, the positive resist is exposed
30 to a laser beam having a well-characterized profile. With a pre-defined sampling rate, the area of the resist film of interest is exposed to the laser

on a finite laser beam would be essentially the same irrespective of whether the laser beam exposure created a convex or concave surface-relief

15 structure. In accordance with the invention, it has been found that this belief is not true and in fact by fabricating the initial master for a convex microlens array as a concave surface-relief structure, high fill factors (e.g., fill factors equal to or essentially equal to 100%) and high focusing efficiencies (e.g., focusing efficiencies at least above 75%) are achieved. A
20 detailed discussion of how this combination addresses the convolution problem is presented below.

To create a mold usable in high volume replication, intermediary replication steps are generally necessary because resist films are usually unsuitable for large-volume replication. For example, the concave surface-
25 relief structure can be used to prepare an intermediate master (intermediate mold), which is of convex form. The intermediate master can then be replicated once more to provide a final master (final mold), now in concave form. Large-volume replication is then possible with the final concave master so that the final array has a convex form and provides a
30 high fill factor and a high focusing efficiency.

The array need not be limited to regularly periodic arrangements, such as square or hexagonal arrays, but may assume any general arbitrary form, as dictated by the requirements of the design. Furthermore, the lens shape need not be the same and can, in fact, vary for every microlens in the array. For example, the techniques of the present invention can be used to produce the configurations and distributions of microstructures set forth in the above-referenced, commonly assigned U.S. Patent Application entitled "Structured Screens for Controlled Spreading of Light."

A fact of importance in the present invention is that the tops of the concavities of the concave surface-relief structure formed in the positive resist film are preferably aligned or vary slowly for any neighboring elements. If this guideline is not satisfied, accurate profiles may only be produced over a portion of the array, reducing both the fill factor and the focusing efficiency of the array.

V. BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a top view of a lens array with a fill factor less than 100%.

FIG. 2 shows a glass substrate with a photosensitive film deposited on its surface.

FIG. 3 shows the scanning of a laser beam over a photosensitive film creating a region of distinct chemical properties (latent image).

FIG. 4A and FIG. 4B show the effect of convolution in the fabrication of convex structures.

FIG. 5A and FIG. 5B illustrate the interaction of a hard fabrication tool in relation to a convex and concave array, respectively.

FIG. 6 illustrates a technique for estimating the focusing efficiency of the microlens units of an array fabricated in convex form.

FIG. 7A and FIG. 7B show experimental plots of identical microlens profiles fabricated in convex and concave forms, respectively.

FIG. 8 and FIG. 9 illustrate surface-relief structures having concave cavities formed in a positive photoresist where the edge boundaries of the cavities are aligned with the top surface of the photoresist.

every point in such a fashion that a latent image of the negative of the
desired convex microlenses is imprinted in the resist in the form of a
15 chemical transformation of the resist material.

To obtain a surface-relief structure the chemically modified resist
film undergoes a development process, which consists of exposure to a
solution of, for example, a standard alkali developer for a period of time
that varies with the total thickness of the array. Deeper arrays require
20 longer development times. For a resist of the positive type, the development
process removes the exposed areas, leaving the unexposed areas.

According to the inventive process described herein, each microlens
in the array needs to be produced in the positive photoresist in concave
form. Only in this way is it possible to reduce significantly the rounding
25 effect observed when microlenses are fabricated in convex form. This is so
because the fabrication process itself introduces features into a surface-
relief profile that are undesirable.

Given the mathematical description of the desired surface-relief
structure and the writing laser beam, the relief structures obtained by
30 exposure of a resist film are generally described as the convolution of the

desired surface function with the laser beam function. The operation of convolution can be mathematically described by the following relation:

$$F(x, y) = \iint_S f(x', y') g(x' - x, y' - y) dx' dy', \quad (1)$$

5

where f represents the mathematical function describing the desired surface relief, g represents the mathematical form of the writing laser beam, S represents the fabricated surface area, (x, y) denotes a point on the surface of the photosensitive film, and F represents the final surface shape.

10 The validity of Eq. (1) relies on the assumption that the interaction of the laser beam and the photosensitive film is linear, in the sense that the response of the film is in direct proportionality to the intensity of the laser exposure and that the superposition of several beams has a simple additive effect. To a good approximation this assumption is correct and can be
15 observed in surface-relief structures fabricated in convex form, that is, structures that protrude from the resist surface as illustrated in FIGS. 4A and 4B.

 The fact that the expected convolution effects are readily observed in convex structures has led to the general belief that the same type of
20 behavior would happen for concave shapes. In fact, if one uses Eq. (1), and notes that to obtain the concave shape one simply needs to multiply the convex shape by -1 and add a constant, then it would appear that the final shape should be the same for both the concave and the convex shapes, except for the change in sign.

25 However, it turns out that the interaction between the laser beam and the photosensitive film is not linear and, therefore, the convolution relation can describe the fabrication process only approximately. In fact, in accordance with the invention, we have discovered that the laser writing process is more akin to the fabrication of devices by means of hard
30 mechanical apparatuses such as diamond tools.

asymmetry when considering convex and concave shapes. This surprising result enables the fabrication of fully-packed convex microlens arrays, as
15 opposed to previous methods that can only guarantee accurate profiles over a fraction of the aperture of the array in a fully-packed arrangement.

Importantly, the laser-writing process when used to make concave surface-relief structures not only achieves the advantage of mechanical ruling devices for concave structures but also offers significant capabilities
20 that go beyond those of mechanical ruling methods. For instance, there is virtually no limitation regarding the size or shape of microlenses made with the laser-writing process. Also, the size of the mechanical tool itself determines the extent of the boundary region between neighboring microlenses. With laser writing, this region can be arbitrarily reduced.

25 The ability to preserve a concave surface-relief shape from the apex of the structure to its very edge at the boundary of a neighboring concavity allows for the fabrication of arrays of convex microlenses of high focusing efficiency. It does so since it allows the final convex microlenses to have a fully-packed arrangement. In contrast, if the array is directly produced in
30 convex form, independent of whether one uses a mechanical tool, a laser tool, or other process, the boundaries of two neighboring microlenses cannot

be usefully employed for focusing and thus the array will have a reduced focusing efficiency.

This deficiency of producing an array in convex form, whether by means of a mechanical or a laser tool, is illustrated in FIG. 6. In this figure, the desired microlens shape is represented by curve 61 with an area available for focusing represented by the parameter A. However, due to the fabrication, the actual microlens shape turns out to be that given by curve 62 and the area available for focusing now being represented by the parameter B. The observed rounding effect at the boundaries of the microlenses diverts the incident illumination to locations other than the focal point of the microlens. Therefore, only area B becomes available for focusing. In this way, the estimated focusing efficiency of the microlens η can be written as

$$\eta = \left(\frac{B}{A} \right)^2 \times 100\%. \quad (2)$$

15

With the prior art, B is always less than A so that the focusing efficiency is less than 100%. With the current inventive process, the initial surface-relief structure is written in concave form so that sharp boundaries between lenses are well reproduced in the final microlens array. When the concave master is replicated one obtains a convex array such that B essentially equals A. Consequently the focusing efficiency is essentially 100%.

Experimental studies have confirmed the above analysis, especially in the case of convex microlenses of high numerical aperture (fast lenses) where light is focused at large angles. FIG. 7A shows the case of an array of microlenses with diameter equal to 50 μm fabricated in convex mode. The boundaries between microlenses are clearly rounded and cannot be efficiently used for focusing. The estimated efficiency for each microlens in this array is 50%.

between the mechanical ruling and the laser writing starts to fail when neighboring concavities present a relative vertical offset, such as, the
15 "piston" of the above-referenced, commonly assigned patent application entitled "Structured Screens for Controlled Spreading of Light." For some types of screen applications, the reduced efficiency might be acceptable. In other cases, the loss in focusing efficiency is intolerable.

As shown in FIG. 9, the requirement of alignment between the top of
20 the concavities of the concave surface-relief structure is fully compatible with the requirement of some arrays that the focusing properties of the individual microlenses vary randomly. In this case, the vertices of the concavities do not align, only their tops. A similar principle applies for two dimensional arrays.

25 After development, the surface-relief structure obtained with the laser exposure provides a first mold that can be used for replication. If the material that constitutes the photosensitive film is suitable for replication, than replicas of that master can be readily fabricated in convex form. If concave replicas are required, an intermediate replication step is necessary
30 whereby a convex tool is formed, which is ready to produce concave arrays. Typically, the photosensitive film is not suitable for many replications and,

as a result, molds are preferably made of, for example, stronger plastic resins.

A representative replication process is illustrated by the sequence shown in FIG. 10A through FIG. 10C.

- 5 FIG. 10A shows the initial surface-relief structure 101 in concave form with the tops aligned. The substrate, e.g., glass substrate, is identified by the reference number 102. FIG. 10B shows another substrate 103 on which a plastic resin 104 has been deposited. This resin will be one more suitable than a photoresist for use or as an intermediate replication tool.
- 10 FIG. 10C shows the result of replication of the intermediate replication tool of FIG. 10B to generate the desired array of convex microlenses 105.

- Sequences similar to that shown in FIG. 10 can be used to make high efficiency, high fill factor arrays of concave microlenses with again the initial surface-relief structure being formed in a positive photoresist in
- 15 concave form.

- Although specific embodiments of the invention have been described and illustrated, it will be apparent to those skilled in the art that modifications and variations can be made without departing from the invention's spirit and scope. The following claims are thus intended to cover
- 20 the specific embodiments set forth herein as well as such modifications, variations, and equivalents.

- (ii) produce a further master used to form the microlens array, and/or
- (iii) produce the first of a series of further masters used to form the microlens array;

wherein said microlens array comprises at least two convex microlenses at adjacent unit cells so that the master comprises at least two concavities at adjacent unit cells.

2. The method of Claim 1 wherein said microlens array comprises only convex microlenses so that the master comprises only concavities.

3. The method of Claim 2 wherein the master lies between a first plane and a second plane, the concavities extend into the master in the direction from the first plane towards the second plane, and the maximum sag of each concavity is at the first plane.

4. The method of Claim 2 wherein the master lies between a first plane and a second plane, the concavities extend into the master in the direction from the first plane towards the second plane, and the location of the maximum sag of each concavity relative to the first plane varies between at least some adjacent unit cells at a sufficiently slow rate so that

the focusing efficiency of the microlens array is not reduced below 75 percent.

5. The method of Claim 1 wherein the master lies between a first plane and a second plane, the at least two concavities extend into the master in the direction from the first plane towards the second plane, and the distances between the apexes of the at least two concavities and the first plane are different.

6. The method of Claim 5 wherein said distances are randomly distributed.

7. The method of Claim 1 wherein at least one of said at least two concavities is anamorphic.

8. The method of Claim 1 wherein the microlens array has a focusing efficiency of at least 75 percent.

9. The method of Claim 1 wherein the microlens array has a focusing efficiency of at least 85 percent.

10. The method of Claim 1 wherein the microlens array has a focusing efficiency of at least 95 percent.

11. The method of Claim 1 wherein the fill factor of the microlens array is at least 90 percent.

12. The method of Claim 1 wherein the fill factor of the microlens array is at least 95 percent.

13. The method of Claim 1 wherein the fill factor of the microlens array is substantially equal to 100 percent.

14. A microlens array comprising a plurality of unit cells and a plurality of microlenses, one microlens per unit cell, said array having a focusing efficiency of at least 75 percent.

15. The microlens array of Claim 14 wherein the array has a focusing efficiency of at least 85 percent.

16. The microlens array of Claim 14 wherein the array has a focusing efficiency of at least 95 percent.

24. The structure of the unit cell is

25. The structure of the unit cell is
close packed.

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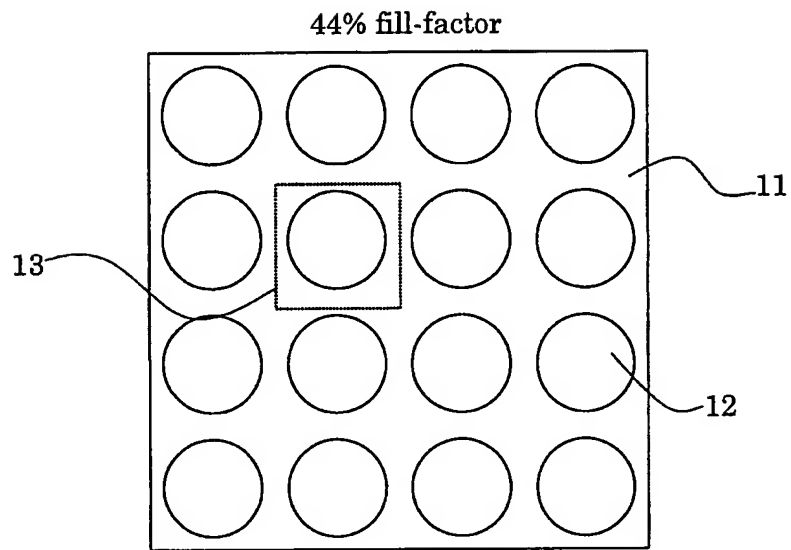


FIG. 1

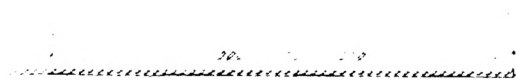


FIG. 2

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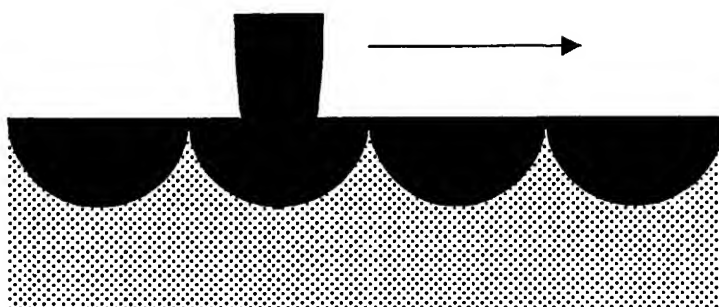


FIG. 3



FIG. 4A

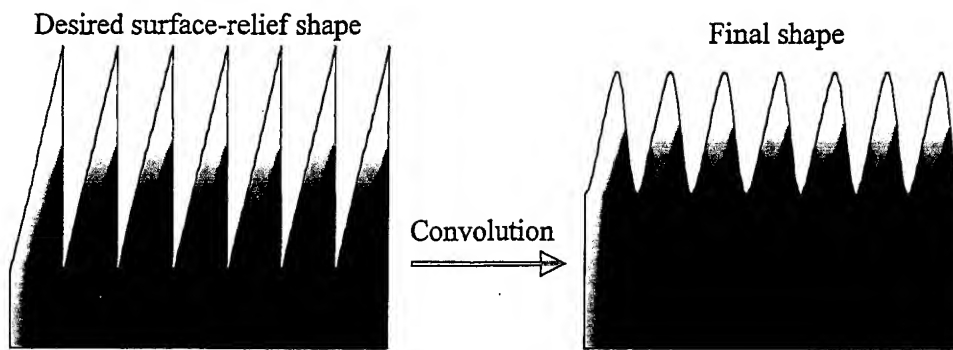


FIG. 4B

5/11

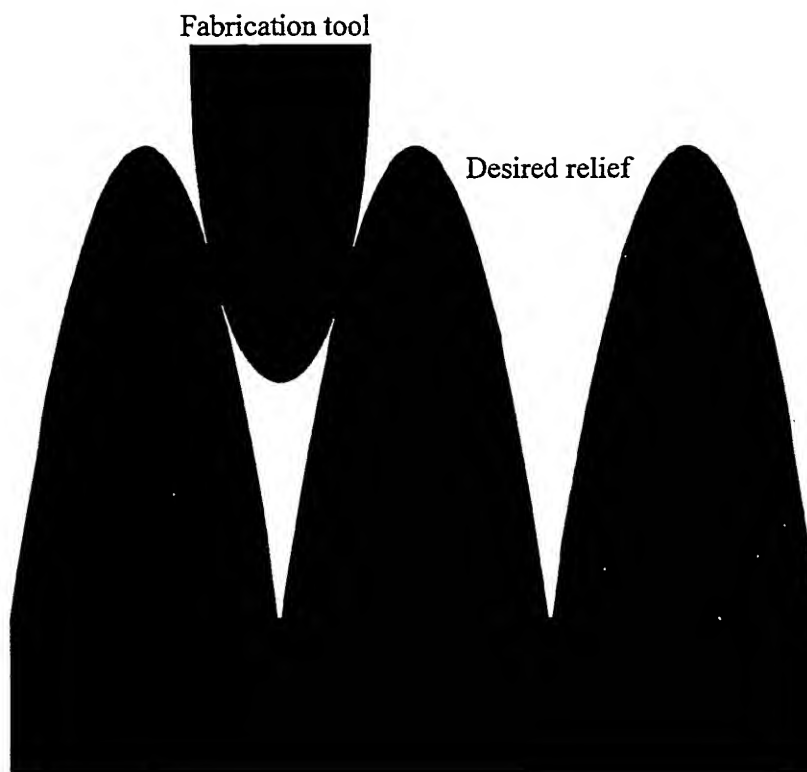


FIG. 5A

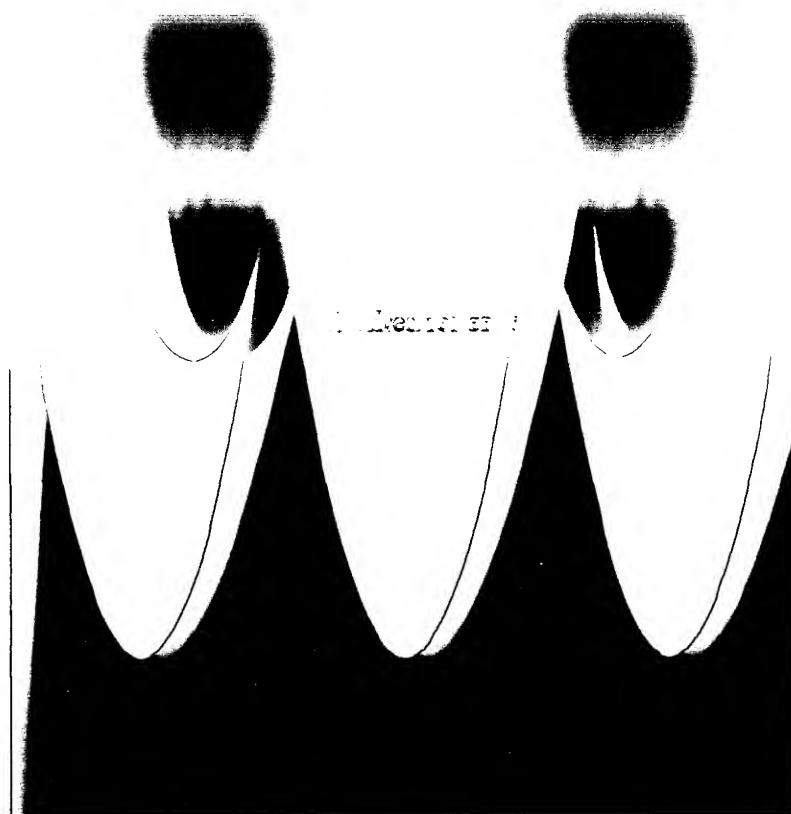


FIG. 5B

7/11

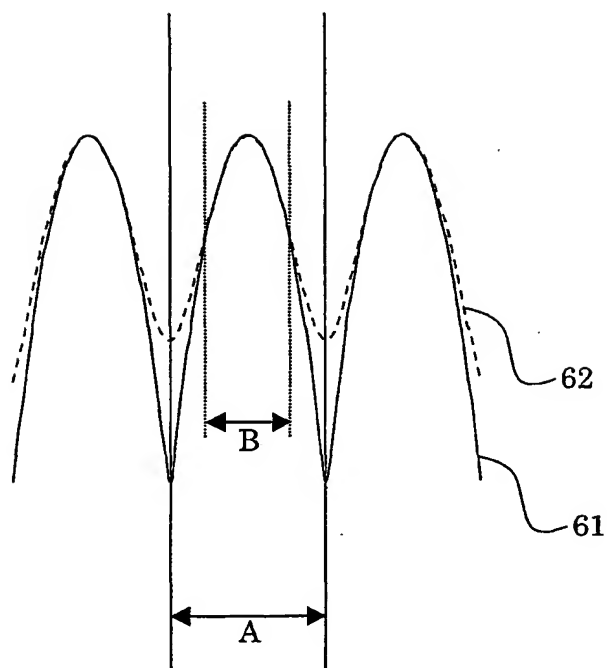


FIG. 6

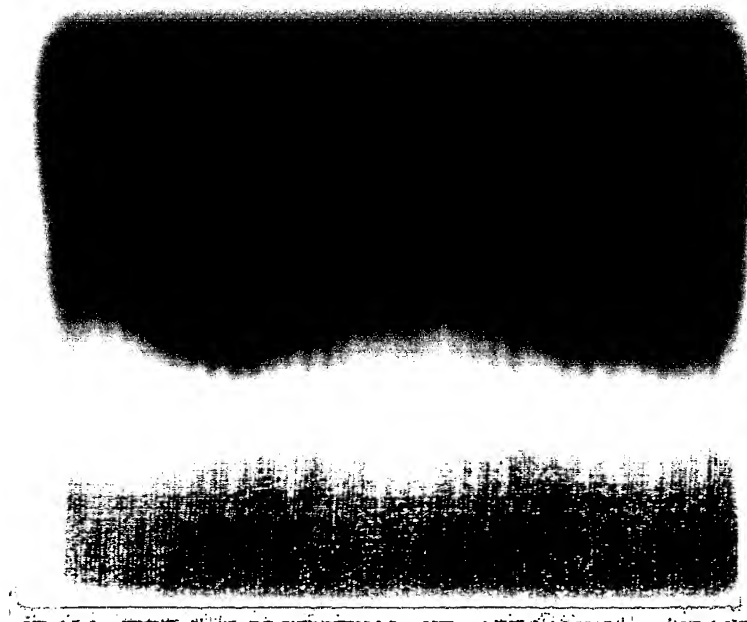


FIG. 7A

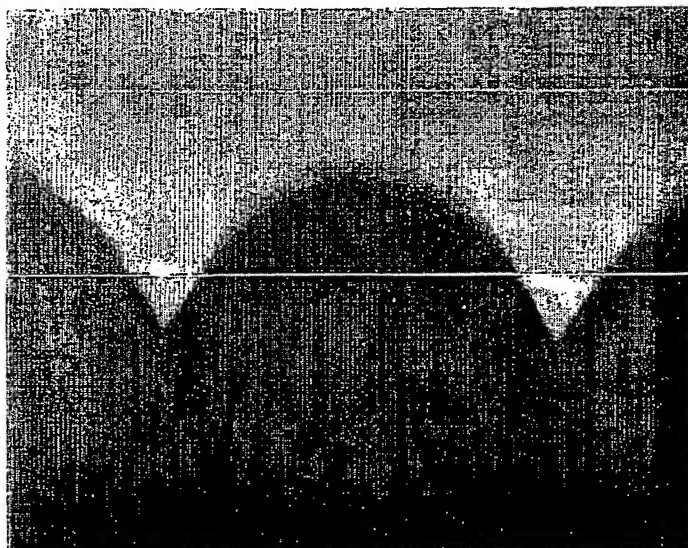


FIG. 7B

9/11

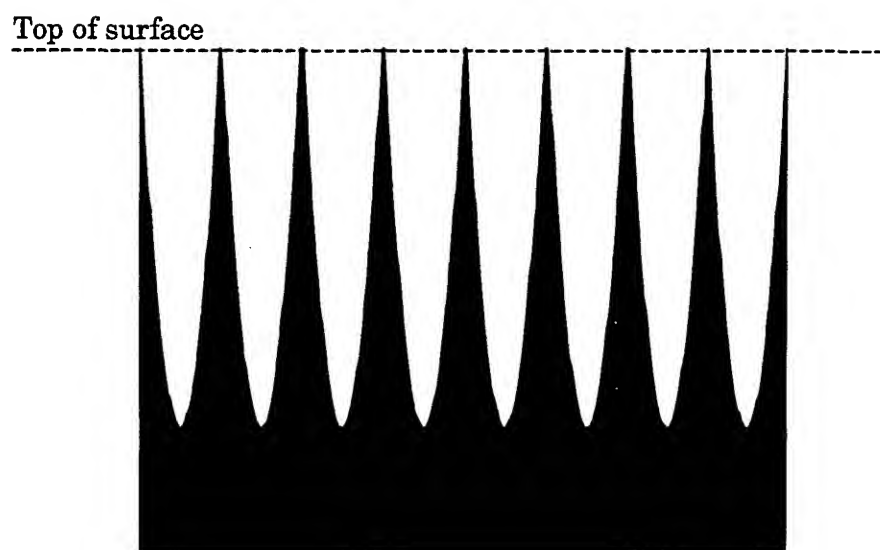


FIG. 8

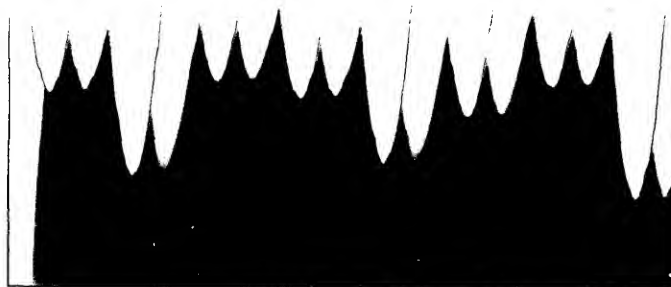


FIG. 9

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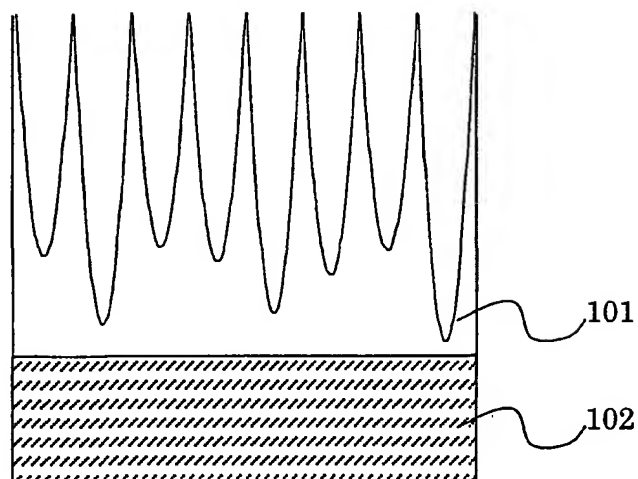


FIG. 10A

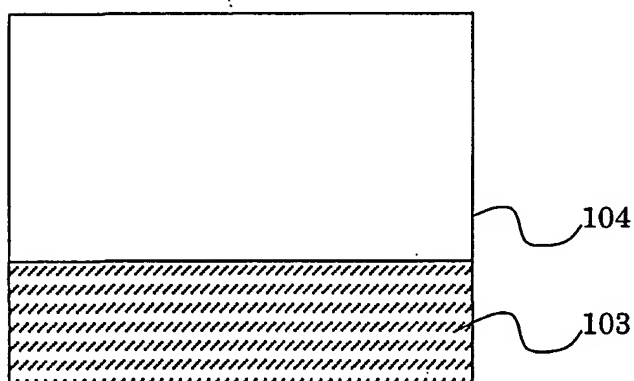


FIG. 10B

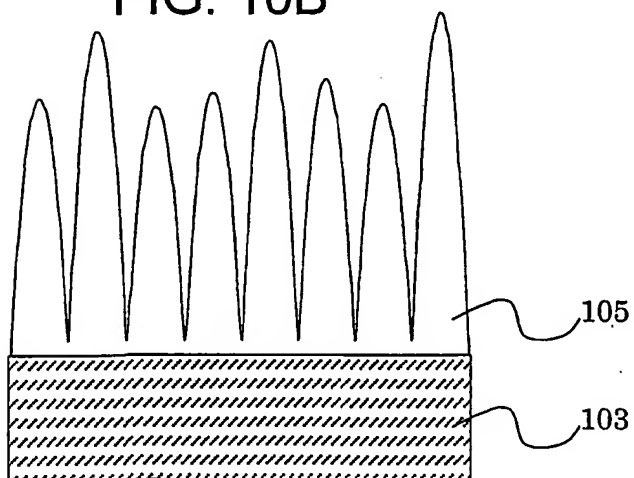


FIG. 10C

X	US 5,808,637 A (KURTZ et al.) 15 September 1998 (15.09.1998) figure 1 and accompanying text.	14-20 and 23
X	US 5,439,621 A (HOOPMAN) 08 August 1995 (08.08.1995) see figures and column 9/lines 15-21 and column 5/lines 1-13 and 42-48.	14 - 23
Y		1-23
Y	US 5,728,509 A (EDA et al.) 17 March 1998 (17.03.1998) figures 3a-d, example 3 and example 6.	1-23
Y	US 4,372,649 A (KELLIE) 08 February 1983 (08.02.1998) column 5/lines 64 through column 5/line 6.	1-13
Y	JP 03-214101 A (NIPPON SHEET GLASS CO. LTD.) 19 September 1991 (19.09.1991) figure s 3 and 5 and corresponding text.	1-23

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Date of the actual completion of the international search 23 October 2001 (23.10.2001)		Date of mailing of the international search report 16 NOV 2001	
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C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 11-344602 A (SEIKO EPSON CORP.) 14 December 1999 (14.12.1999) figure 9 and corresponding text.	1-13
Y	US 5,867,307 A (MYERS et al.) 02 February 1999 (02.02.1999) column 7/line 54 through column 9/line 8.	1-13
Y	JP 54-083846 A (none) 04 July 1979 (04.07.1979) see figures.	1-23
Y	JP 03-122614 A (MATSUSHITA ELECTRIC IND. CO. LTD) 24 May 1991 (24.05.1991) figures 1a-d and corresponding text.	1-13
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Y	US 5,148,322 A (AOYAMA et al.) 15 September 1992 (15.09.1992) column 7/line 53 through column 8/line 12.	1-13

